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Measurement of Infrasound from the Marine Environment

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ADMINISTRATIVE INFORMATION

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EXECUTIVE SUMMARY

OBJECTIVE

The objective of the Measurement of Infrasound from the Maritime Environment project team at Space and Naval Warfare Systems Center Pacific (SSC Pacific) is to develop an infrasound sensing capability that can operate from the maritime environment. Infrasound monitoring stations are normally situated on land-based sites. Because two thirds of the earth's surface is composed of oceans, a functional maritime-based infrasound sensing capability would greatly enhance the ability to monitor natural and anthropogenic sources of infrasound around the world. The technical challenges include sensor motion, wind noise, composing arrays of sensors, and survivability in the ocean environment. This report outlines the challenges and focuses on a potential solution for overcoming the negative impact of ocean-induced heave motion on the infrasound sensor.

RESULTS

Ocean heave, as measured by the sea surface spectrum, is shown to occupy a significant portion of the infrasound receive frequency band. Measurements were taken with a microbarometer fielded on board a ship during an at-sea experiment. The collected sound pressure data shows the interference effects of ocean heave, which are due to the change in the background atmospheric pressure as the sensor moves up and down. An external inertial measurement unit (IMU) was used to estimate the heave, and was highly correlated with the pressure interference signal.

RECOMMENDATIONS

The project team recommends that SSC Pacific continue to develop a heave interference cancellation system for the microbarometer. This effort will involve implementing an improved robust IMU for better accuracy. Once an external high-quality estimation of heave is obtained, an adaptive interference cancellation algorithm will be developed and applied. Additional data collection and experimentation is required. Once this system has been demonstrated, approaches to counter wind noise and operate multiple sensors as an array will be developed.

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BACKGROUND

Infrasound is very low frequency airborne acoustic energy that is inaudible to human beings. Infrasound acoustic waves occupy the frequency band of about 3.3 mHz to 20 Hz. Natural sources of infrasound include earthquakes, meteors, volcanoes, tsunamis, auroras, and ocean swells [1]. Among anthropogenic sources are atmospheric and underground nuclear explosions. Because of its low frequency, infrasound waves experience little attenuation, and can therefore propagate to, and be detectable from, very long distances. Although the signals are inaudible, they may be detected using advanced infrasound sensing technology at ranges of 100s to 1000s of kilometers. The Comprehensive Nuclear Test Ban Treaty Organization (CTBTO) operates a worldwide network of about 60 land-based infrasound monitoring stations whose primary purpose is to detect nuclear test explosions [2]. These stations also routinely detect the other natural and anthropogenic sources of infrasound when they occur at great distances.

Wide global infrasound coverage is obtained using the CTBTO land-based network. However, two thirds of the earth's surface is composed of oceans, and no capability yet exists to monitor infrasound from sensors fielded in the maritime environment. The challenges of developing such a capability may be significant; however, if overcome, such capability could provide infrasound coverage where it does not exist, or where it is unreliable due to variable environmental conditions. In addition, event detection redundancy achieved by multiple monitoring stations along different propagation paths is a desirable capability that could improve event detection confidence, classification information, and localization and tracking performance. Such an expansion of infrasound monitoring capabilities may also provide more complete environmental characterization important for understanding infrasound performance worldwide.

The sensor most often employed to measure infrasound is the microbarometer, which provides very accurate measurements at very low infrasonic frequencies [1]. It is also suitable for outdoor use, where it can maintain performance during exposure to the elements, including high humidity conditions. Land-based monitoring sites are normally composed of multiple (up to 10) sensors spaced a few hundred meters apart, each with a wind filtering system and forming an array. The station includes data acquisition and communication technology and the required electric power for operations. The systems are calibrated appropriately for their installed locations.

CHALLENGES OF THE MARITIME ENVIRONMENT

The challenges of fielding microbarometers in a maritime environment, compared to a land-based site, are anticipated as described in the following subsections.

Sensor Motion

Maritime deployment will expose the sensor to motion effects, since the platform is moving with ocean swell and waves. The sensor may experience motion along 6 degrees of freedom: surge, sway, yaw, pitch, roll, and heave. The most significantly impacting of these is likely the heave motion, as even small changes in altitude will induce a change in ambient atmospheric pressure, causing an interference signal against which infrasound signals are to be detected.

Wind

Wind is a main contributor to the infrasound sensor's noise background level. Maritime environments are characteristically windy environments, and maritime deployment schemes will therefore require additional mitigation or compensation methods. Possible approaches are to develop suitable shrouds, wind filters, or adaptive wind noise cancellation algorithms, tailored for use in a maritime environment.

Multi-element Arrays

To validate infrasound detections and determine their direction, arrays of infrasound sensors are usually employed. Since the intersensor spacing for infrasound is on the order of several 100's of meters, maritime deployment will require multiple platforms, all of which may be moving relative to one another. Therefore, sensor element positions must be tracked over time. Another implication is that this will require some communication capability to send the sensors' data to a fusion center for array processing.

Survivability

The maritime environment is a harsh operating environment. Exposure to extremes in weather and the effects of water and salt require significant efforts in ocean engineering to ensure system survivability and ensure a persistent operational capability.

INFRASOUND SENSOR HOSTS IN THE MARITME ENVIRONMENT

Infrasound sensors to be deployed in the maritime environment may be hosted on the following platforms described in the following subsections. While all maritime platforms will be subject to all 6 degrees of motion, the effects of surge, sway, and yaw are likely to be dominated by those of roll, pitch, and heave.

Ships

This option has the highest mobility, allowing for relocation of the sensor to different areas of the ocean in the least amount of time. The sensor will be subject to heave, pitch, roll, and ship vibration, all potential negative impacts on its performance. On board ships, there may be more options available to mitigate the effect of wind, through intelligent placement on board and/or with the design of shrouds. The practicality of using a set of ships for an infrasound array is dubious. However, because they must operate in close proximity, they are hugely expensive to operate, and will surely have higher priority tasking, making them unsuitable for persistent infrasound sensing missions.

Ocean Buoy(s)

Normally, ocean buoys are moored to the ocean bottom and could potentially provide a persistent, autonomous, but non-mobile infrasound monitoring option. They would be subject to heave, pitch, and roll, and some lateral drift constrained by the mooring's watch circle, but would likely experience less vibration and seismic interference than ships. Wind mitigation efforts may be more challenging due to the limited buoy real estate and the continuous exposure to the environment. Multiple moorings in the close proximity suitable for an infrasound array (100's of meters) may be prohibitive due to risk of tangling and the array shape will dynamically change due to current drift. Conventional buoys will be subject to ocean surface waves and swell, resulting in sensor heave, pitch and roll. A Spar buoy is a type of buoy with a tall, thin shape and which is very stable in the ocean, and much less sensitive to heave, pitch, and roll, creating a better potential platform for an infrasound sensor. Drifting buoys would not maintain the proximity needed over time for an array configuration.

Unmanned Surface Vehicle (USV)

Autonomous ocean-going (surface and underwater) vehicles can now host various sensor payloads. The Waveglider SV2 is a small surfboard-sized USV manufactured by Liquid Robotics (Figure 1), which can be deployed for an extended time and provide a persistent sensing capability [3]. It harvests wave energy to provide some thrust, enabling it to maintain position in currents or even make slow headway toward a distant destination. The unit includes solar panels that are used to power various instruments and payloads. As an infrasound sensing platform, the USV would share many of the characteristics of an ocean buoy, but avoid the complications of moorings and have some control over its mobility. It will still be subject to heave, pitch, and roll.

Table 1. Potential performance indicators for different maritime platforms.

Parameter	Ships	Conventional Buoys	USVs
Motion	Heave, Pitch, Roll	Heave, Pitch, Roll (if conventional buoy, but minimized if Spar buoy)	Heave, Pitch, Roll
Vibration	Significant	Minimal	Minimal
Wind	Low	High	High
Array	Costly	Low	Low
Autonomy	No	Yes	Yes
Mobility	High	None	Medium
Survivability	High	Medium	Low
Persistence	Low	Med-High	Med

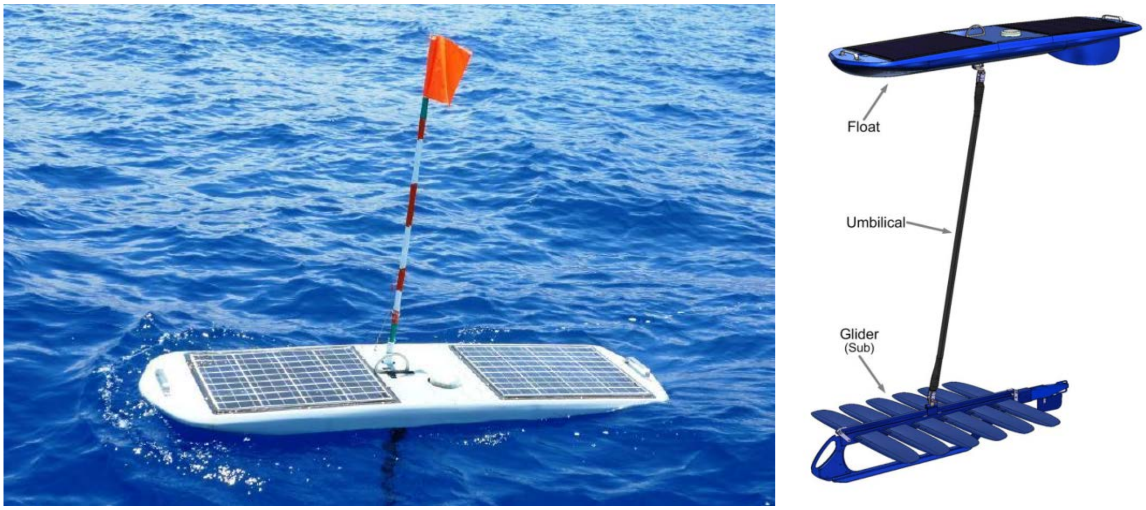


Figure 1. Liquid Robotics Waveglider.

ATMOSPHERIC EFFECTS ON INFRASOUND

INFRASOUND PROPAGATION

The characteristics of the atmosphere will govern how infrasound propagates through the environment. Infrasound will refract (bend) depending on the sound velocity profile (sound velocity vs. altitude) for the environment.

The speed of sound in the atmosphere is given by [1]:

$$c_{eff} = \sqrt{\gamma_g RT} + \hat{n} \cdot \boldsymbol{u}, \tag{1}$$

where $\gamma_g R$ is the product of specific heats ratio and the gas constant for air (typical values are 402.8 $m^2 s^{-2} K^{-1}$), T is the absolute temperature, $\boldsymbol{u}$ is the wind, and $\hat{n}$ projects the wind into the source-observer direction. Temperature is the dominant effect, which varies with altitude.

Figure 2a and 2b show a site about 100 nmi west of San Diego, California, near San Clemente Island and its corresponding sound velocity profiles (overlaid) for the month of June along a westward looking direction. These were extracted from the NRL Ground to Space (NRL-G2S) and the Horizontal Wind Model (HWM) databases by the InfraMap infrasound modeling tool [4]. The sound velocity profiles show velocity minima near the tropopause (transition point between the troposphere and stratosphere, around 18 km) and the mesopause (transition point between the mesosphere and thermosphere, around 90 km). These are caused by temperature inversions in the upper atmosphere. Infrasound generated from the earth will propagate laterally and upward with little attenuation until it refracts back to earth from the stratosphere or thermosphere. It then will reflect from the earth's (land or ocean) surface and continue to propagate. Figure 2c shows the output of InfraMap acoustic ray propagation model, and shows that for this environment, the sound energy propagates back to the earth starting at about a 200-km distance. The strength of the infrasound signal at a sensor will depend on the range of the sound source to the sensor, refraction effects (that produce zones of increased and reduced intensity–shadow zones), and the frequency of the sound (lower frequencies attenuate less than higher frequencies). The InfraMap modeled transmission loss is shown in Figure 2d.

ALTITUDINAL PRESSURE CHANGES

Infrasound waves are longitudinal acoustic pressure waves. Infrasound pressure fluctuations for sources of interest are small compared to the ambient pressure. The ambient pressure at sea level is referred to as the atmospheric pressure (or hydrostatic pressure), which is due to the accumulated weight of the air in all of the atmosphere layers above. Its nominal value is 101,325 Pa (or 1 atm). The received pressure wave signals for various infrasound sources range from about 5,000 to 1,000,000 times smaller than the ambient pressure.

Ambient pressure decreases with altitude according to

$$P = P_0 \left(1 - \frac{Lh}{T_0}\right)^{\frac{gM}{RL}}, \tag{2}$$

where P_0 is sea-level atmospheric pressure (in Pa), h is the altitude, L is the temperature lapse rate for dry air, T_0 is sea level temperature, g is gravitation acceleration, M is the mass of dry air, and R is the universal gas constant. This function is shown in Figure 3, where we see its non-linear nature at high altitude.

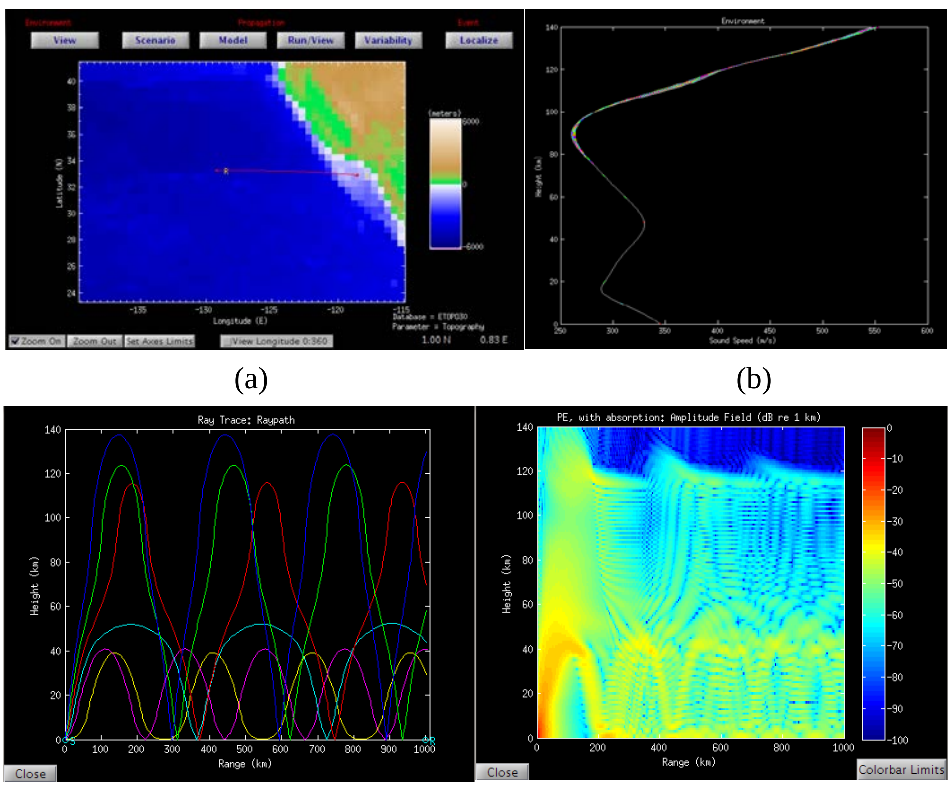
Near sea level, where the infrasound sensor is to be located, changes in pressure due to slight changes in ocean heave are approximated by

$$\Delta P = -\rho g \Delta h, \tag{3}$$

where ρ is the air density. For a standard atmosphere (1 atm and 0 °C), $\rho = 1.2754\ \mathrm{kg}/m^3$, and

$$\frac{\Delta P}{\Delta h} \approx -12.5\ \frac{Pa}{m}. \tag{4}$$

Therefore, at sea level the pressure gradient with altitude is approximately -12.5 Pa/m. The implication is that an infrasound sensor, deployed in the maritime environment and moving vertically up and down (heaving) with ocean swell, will also measure the pressure fluctuations due to change in ambient atmospheric pressure. This signal is of significant strength, and may potentially obscure and interfere with the detection of actual infrasound signals of interest. If the heave-induced signal and the infrasound signal occupy different and disjoint frequency bands, standard filtering methods will be successful in separating them. However, if the heave frequency spectrum and the infrasound signal spectrum overlap in frequency, then a more sophisticated heave compensation method will need to be applied, as described in later sections.



(a) (b)

(c) (d)

Figure 2. InfraMap modeling example: (a) site near San Clemente Island, (b) sound velocity profile for June at the site, (c) raypath modeling result, (d) PE modeling of transmission loss.

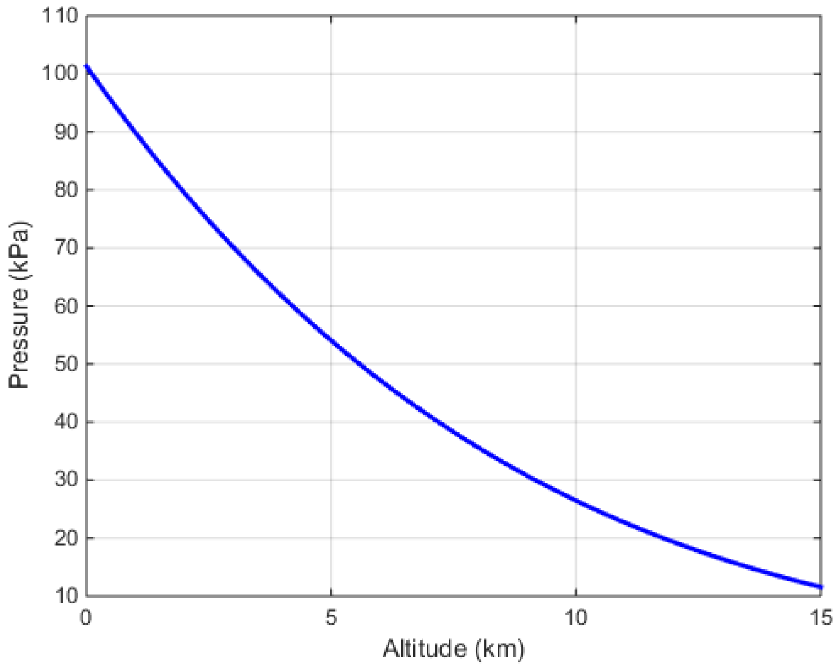


Figure 3. Atmospheric pressure as a function of altitude.

HEAVE IN THE MARITIME ENVIRONMENT

WIND AND OCEAN SURFACE ROUGHNESS

Tides produce cyclical changes in ocean water levels due to the gravitational forces of the moon and sun, the earth's rotation, and other factors. A common tidal effect is a semi-diurnal or diurnal period of fluctuation of several feet or meters water level, and it depends largely on geographic location and the moon's orbit. The frequency of a semi-diurnal tide is about 2e-5 Hz, which is well below the infrasound band propagation lower limit (0.003 Hz). An infrasound sensor exposed to tidal effects will experience ambient pressure fluctuations due to tidal heave; however, these can easily be ignored or filtered out since there are no infrasound signals that low in frequency.

Ocean surface roughness is driven by wind. When winds of certain speed and direction are sustained over enough time, the ocean surface becomes what is termed a "fully developed" sea. Wave size increases with increasing wind speed and increased duration of the wind. The Beaufort scale is an empirical table of sea conditions ("sea state") vs. wind speed [5] that is commonly used by seafarers. Beaufort numbers range from 0 (calm conditions) to 12 (hurricane conditions), from breezes to strong wind to gales in between, with wave heights correspondingly increasing (over a range from 0–15 meters). For the maritime infrasound application, it is important not only to understand the wave heave that the sensor will be subject to, but the wave frequencies (swell periods) associated with them.

The sea surface roughness can characterized as a superposition of many waves with different periods (frequencies), heights, and directions. There may be more than a single source contributing to the generation of waves at any given location. Oceanographers typically use sea surface spectra to characterize the wave energy in the ocean as a function of frequency (and sometimes direction). The frequencies of the sea surface roughness (waves) are inversely related to the period of the swell (i.e., Tp=1/f). "Seas" often refer to localized, chaotic waves with many periods (broad frequency spectra), and can be distinguished from "swell", which is a well-behaved undulation (narrow spectral peak) that has propagated from longer distances. Oceanographic wave buoy instruments are commercially available which produce sea surface spectra by direct measurement of ocean heave [6,7]. Predictions of sea surface spectra can be made using models, for assumed wind speeds. The Pierson-Moskowitz model is a simple, effective model that provides insight into the effects of sea surface roughness as a function of wind speed [8], though more complicated models also exist [9]. Pierson-Moskowitz models a fully developed sea with a sea surface spectrum of the form:

$$S(\omega) = \frac{\alpha g^2}{\omega^5} e^{-\beta(\omega_0/\omega)^4}, \tag{5}$$

where α and β are dimensionless constants given by 7.79x10^{-3} and 0.74, respectively, g is gravitational acceleration, and $\omega_0 = g/U$. U is the wind speed at a reference height of 19.5 meters; however, often a reference of 10 meters is also used.

Figure 4 shows example Pierson-Moskowitz spectra, which are observed to increase in peak energy level, become more peaked, and shift to lower frequencies at higher sustained wind speeds. Other useful parameters can be derived from the spectra, such as the predominant wave period (corresponding the spectral peak) and the "significant wave height" (referred to as $H_{1/3}$ or H_s), which is the mean trough-to-crest wave height of the highest third of waves. This is a commonly used oceanographic parameter, which is consistent with what human observers estimate while at sea. Most wave heights will be less than $H_{1/3}$, but occasionally they may be much higher. The mean wave height is approximately 0.7 times $H_{1/3}$ [10]. These parameters are shown in Figure 5 for various wind speeds.

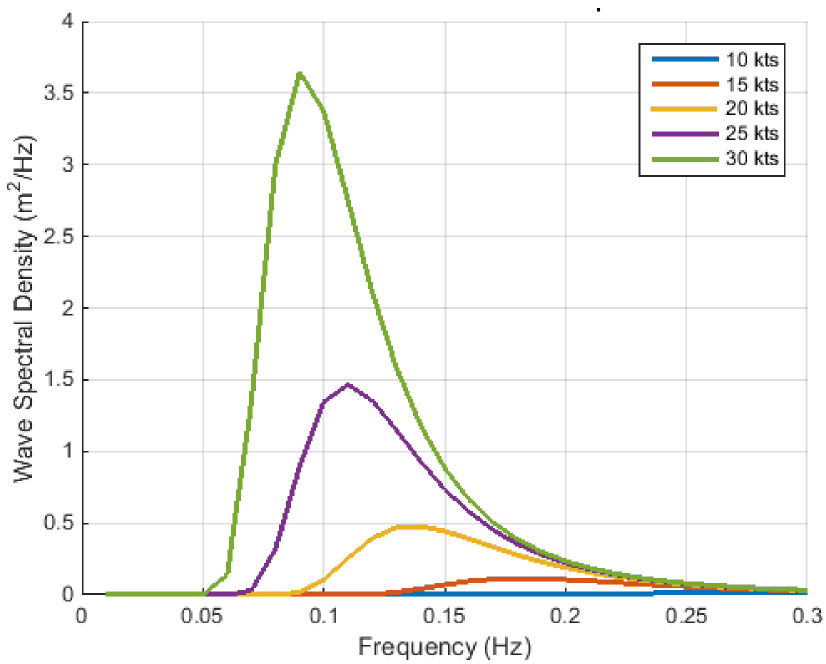


Figure 4. Pierson-Moskowitz sea surface spectra for various wind speeds.

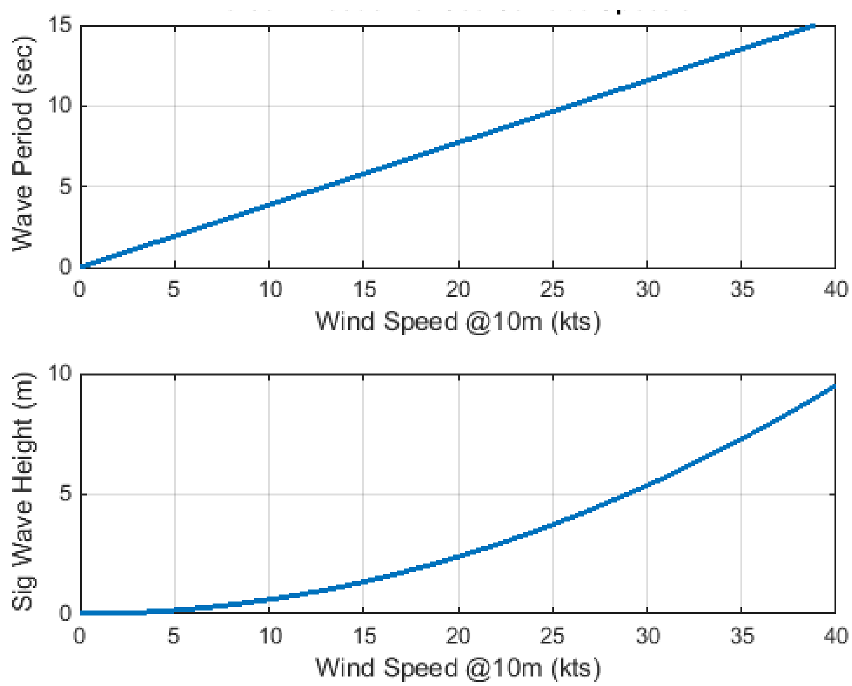


Figure 5. Pierson-Moskowitz predicted wave period and significant wave height as a function of wind speed.

SEA SURFACE SPECTRUM

The ocean will cause the sensor to heave up and down by the magnitude of the wave heights and over a frequency band corresponding to the sea surface spectrum. Most sea surface spectra show that wave energy is contained within a frequency band of 0.03–0.3 Hz (which corresponds to wave periods of 3–30 seconds). Networks of coastal and open-ocean oceanographic buoys provide web access to real-time and historical data, including wind speed/direction, sea surface spectra, etc. [11,12] Figure 6 shows various sea surface spectra, as measured from the Scripps Institute of Oceanography Coastal Data Information Program (CDIP) ocean buoy #067 [11]. This buoy is located off of southern California near San Nicolas Island at a latitude/longitude of 33° 13.261' N / 119° 52.906' W. Four different measurements are shown for different seasons, with different weather conditions. The 2013 spectra (blue and red) show low total energy and a broad spectrum of wave frequencies. The Jan 2014 spectrum shows a mix of two distinct swells. The April 2014 spectrum shows a single, very strong, long wave period swell. The significant wave height and wave period of the spectrum peak is also indicated.

As shown, both predictions and measurements indicate the ocean heave frequencies will be predominately within the 0.03–0.3 Hz frequency band, corresponding to wave periods of about 3–30 seconds. This wave energy band is directly within the infrasound band, and therefore, the potential exists that ocean heave-induced pressure fluctuations sensed by a maritime infrasound sensor will interfere with the monitoring of infrasound signals of interest that are within this band, as depicted in Figure 7. If the infrasound signal band and the sea surface spectrum band do not overlap in frequency, signal processing with conventional filtering techniques (low or high pass filtering) will adequately be able to separate the infrasound signals from the interfering heave-induced signals. However, if their spectra overlap, there will be interference unless the sensor heave is mitigated or compensated in some manner, as discussed in the next sections.

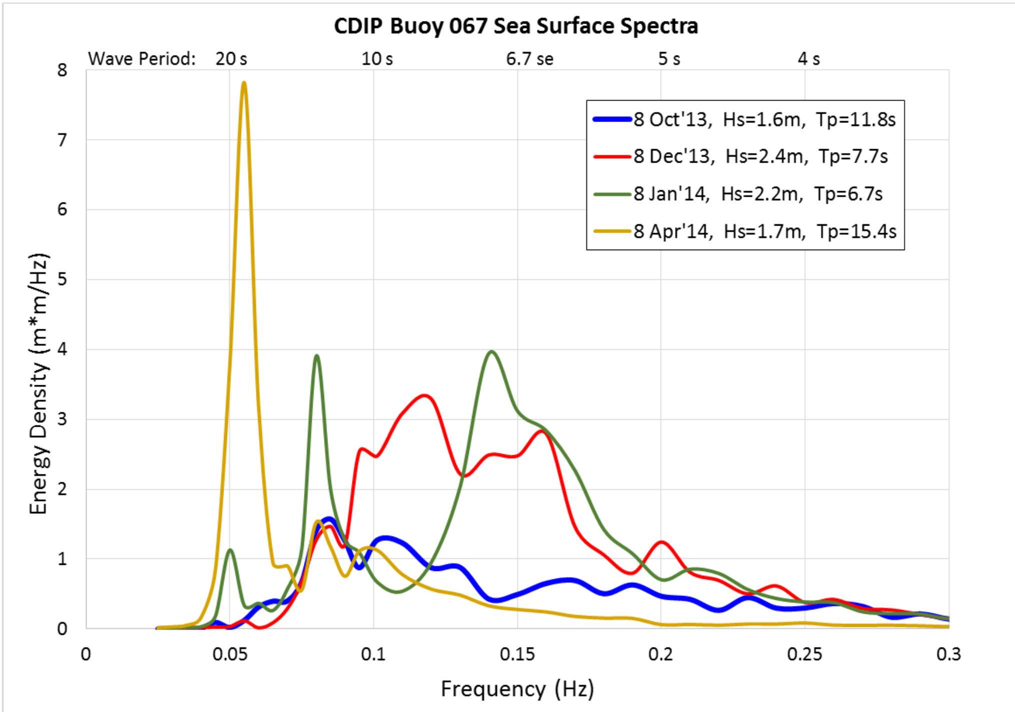


Figure 6. CDIP Buoy 067 sea surface spectra measurements.

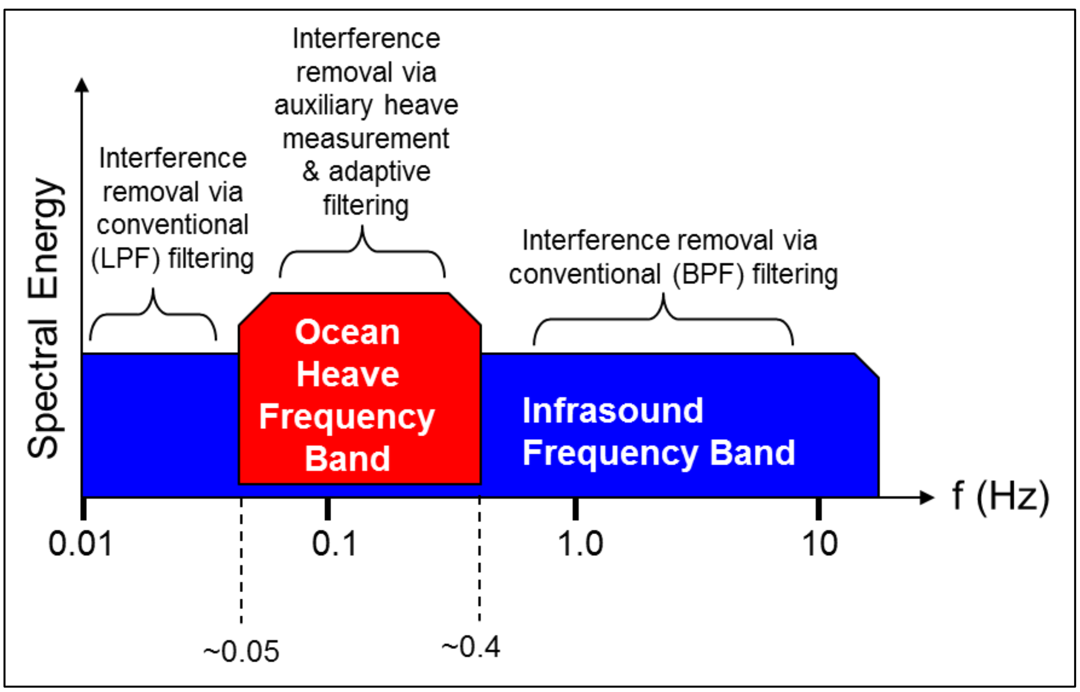


Figure 7. Ocean heave contamination of the infrasound band.

HEAVE MITIGATION

Heave mitigation includes any attempt to reduce or minimize the effect of vertical motion of the microbarometer using physical or mechanical means. One measure that can be taken is to mount the sensor within a mechanical gimbal. This would enable the sensor to remain flat to the horizon, by removing any pitch and roll rotation motion. While this configuration would still be exposed to heave, which is the primary cause of interference for a maritime infrasound sensor, the heave would now be easier to isolate and therefore compensate by being confined to a single axis. Such a mechanical gimbal would need to be carefully designed to withstand long-term exposure to the harsh maritime environment, as the bearings would be susceptible to corrosion, leading to reduced motion mitigation. Additionally, the gimbal would need to be very robust at maintaining a stable, vertical orientation as small errors in the sensor attitude could compound to large heave estimate errors, which may not be possible to guarantee over long periods of time at sea. This mechanical method would still require an accurate, auxiliary heave measurement to act as a reference signal for interference cancellation processing (discussed in detail in the next section).

Another option is the Spar buoy [13]. Spar buoys are designed to provide a stable platform in the water. Because of their long, thin design, there is little surface area subject to wave action. The buoys also have large mass, and therefore are quite insensitive to swell, minimizing exposure to heave. However, due to their large size, they are difficult to deploy, relocate, and recover.

HEAVE COMPENSATION

As an alternative to mitigation, heave compensation instead allows the sensor to experience whatever heave the environment produces and attempts to electronically cancel it out of the resulting signal using either analog or digital processing techniques.

MICROBAROMETER CHARACTERISTICS

We now describe a specific compensation solution to heave-induced interference for a maritime infrasound sensor.

A seismically-decoupled microbarometer has been developed at the University of Mississippi National Center for Physical Acoustics (NCPA) [14]. The technology is also commercially available under a license agreement with the Hyperion Technology Group, Inc. [15]. The sensor is shown in Figure 8. The sensor is based on piezoceramic disks, which provide very flat amplitude and phase response in the infrasound band. Each sensing element is configured with a closed back-volume, and a fore-volume exposed to the atmosphere, as shown in Figure 9. Positive pressure causes the element to be displaced toward the back-volume and a positive proportional voltage is produced. Negative pressure causes the element to be displaced toward the fore-volume and a negative proportional voltage is output. Pairs of sensing elements are mounted with opposite polarities. In addition to pressure changes, acceleration of the sensing elements will cause deflection of the disk and therefore also an output voltage. The pressure due to acceleration is given as:

$$P_a = \frac{ma}{A}, \tag{6}$$

where m is the mass of the element, a is the acceleration, and A is the area of the sensing element. The sensor disk pairs are sensitive to any external, non-horizontal (out of the plane of the mounting frame) accelerations on the element itself (as in the case of gravity) or on the element mounting frame (as in the case of vibration). The components of force on the sensor disks or frame are most impacting in the direction parallel to the sensing axis, which is depicted in Figure 10.

Figure 8. The Hyperion Technology Group's infrasound sensor.

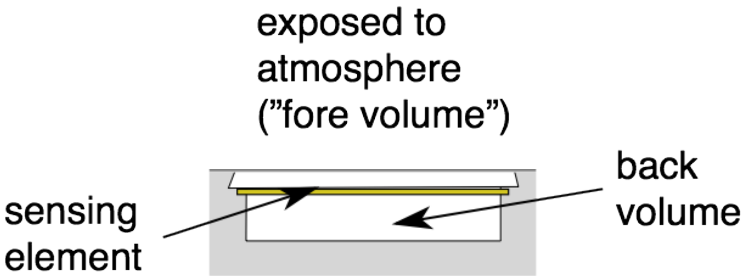


Figure 9. The microbarometer sensing element.

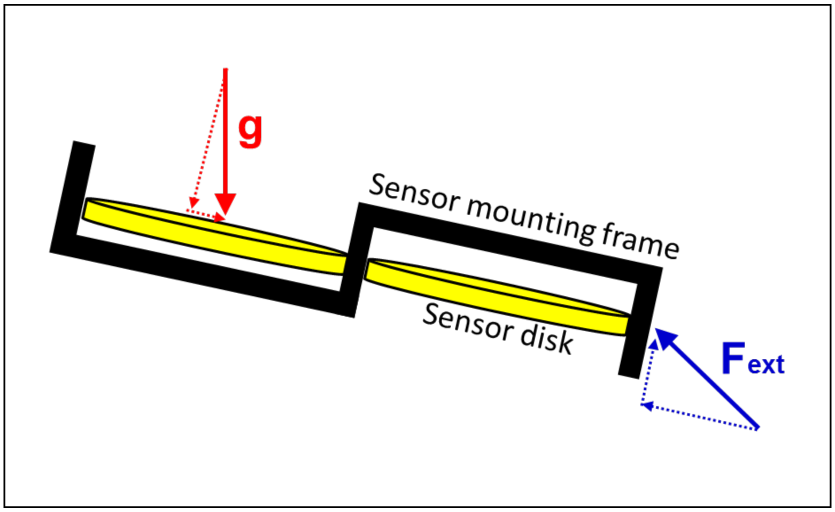


Figure 10. Gravitational forces operating on the sensing disk (red) and external forces operating on the sensor mounting frame (blue).

The microbarometer operates in a 0.001 to 100 Hz operating range, with low power consumption. The calibrated frequency response is shown in Figure 11. The variation from 0.01 to 100 Hz is less than 3 dB. The sensor is A/C coupled, i.e., sensor offsets, dc-biases, or other very low frequency signals with duration longer than about 30 seconds will be reduced.

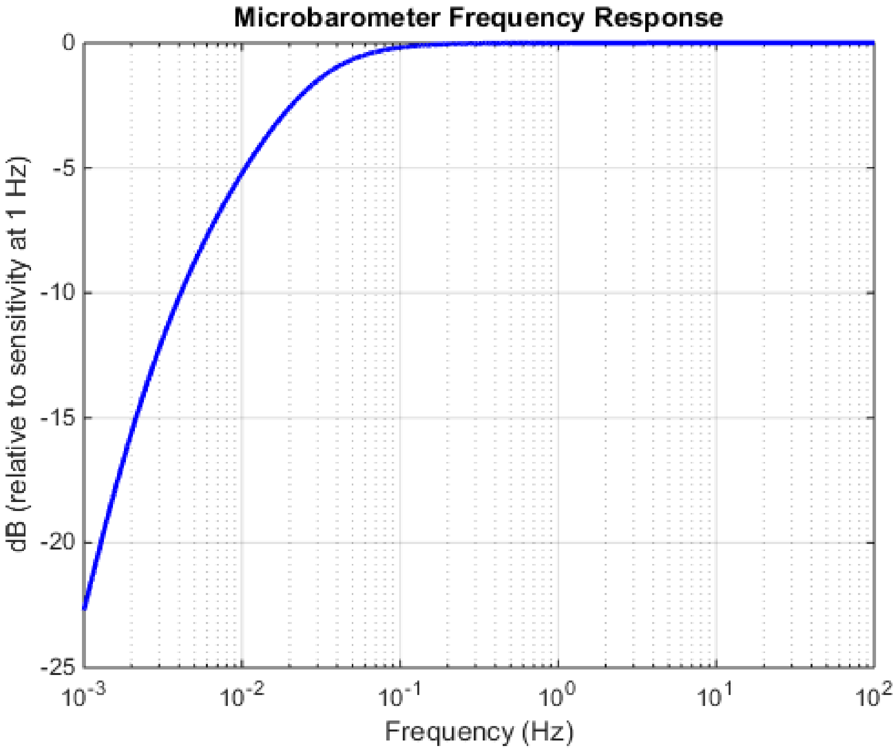


Figure 11. Hyperion microbarometer frequency response curve.

The sensor implements a novel and effective method to suppress seismic or vibrational interference. Two pairs of piezoceramic disks are used in each sensor. Each sensing disk is installed with opposite polarity to the other member of its pair. This approach enables the team to measure and isolate the effects of both acceleration and pressure on the sensor from one another, as will now be described. Each of the disk pairs produces voltage signals as

$$V_1 = S_{p1} \cdot p + S_{a1} \cdot a \tag{7}$$

$$V_2 = S_{p2} \cdot p - S_{a2} \cdot a, \tag{8}$$

where p is the pressure, a is the acceleration, S_p is the sensitivity to pressure (in V/Pa), and S_a is the sensitivity to acceleration (in V*s^2/m) and there is a polarity switch between the two channels. The acoustic pressure is common to both disks independent of the polarity switch, while the acceleration is reversed due to the switch. Solving for pressure and acceleration yields:

$$p = \frac{S_{a2}V_1 + S_{a1}V_2}{S_{a2}S_{p1} + S_{a1}S_{p2}}, \tag{9}$$

$$a = \frac{S_{p2}V_1 - S_{p1}V_2}{S_{a2}S_{p1} + S_{a1}S_{p2}}. \tag{10}$$

The sensitivity to acceleration relative to the sensitivity of pressure has been determined as:

$$G_a = \frac{S_a}{S_p} = 4.27\,\frac{Pa}{m/s^2} \pm 3\% \tag{11}$$

Using this equation, the pressure and acceleration become:

$$p = \frac{S_{p2}V_1 + S_{p1}V_2}{2S_{p1}S_{p2}} \tag{12}$$

$$a = \frac{S_{p2}V_1 - S_{p1}V_2}{2G_a S_{p1}S_{p2}}. \tag{13}$$

The variation of pressure sensitivity among manufactured sensors was shown as negligible; therefore,

$$S_p = S_{p1} = S_{p2} \tag{14}$$

and we obtain

$$p = \frac{V_1 + V_2}{2S_p} \tag{15}$$

$$a = \frac{V_1 - V_2}{2G_a S_p}. \tag{16}$$

Typical values of S_p for the microbarometer are 23.675 mV/Pa.

The design of this sensor effectively mitigates against acceleration when overall displacement is small or negligible (e.g., due to seismic noise or vibration). However, without any other aid, the sensor will still be sensitive to interfering pressure fluctuations if significant vertical displacement occurs. Thus, additional compensation is still required if the sensor is to be mounted on a platform subject to heave motion in the maritime.

EXTERNAL INTEGRATED MEASUREMENT UNIT

One option to compensate for the heave effects is to utilize the acceleration signal of the microbarometer, which would require no additional hardware. This would require the acceleration of the sensor to be completely caused by the vertical (heave) motion of the sensor. In the maritime environment, there will certainly be components of all 6 degrees of motion (pitch, roll, yaw, surge, sway, and heave). Mitigation of pitch and roll motion (as discussed previously by the gimbal), would in theory, result in accelerations only due to vertical heave, with the surge and sway being in its insensitive directions. This acceleration signal could be integrated twice to derive a measurement of vertical displacement. There will, of course, be some errors in the absolute vertical position of the sensor due to measurement drift error, and it is unknown if these would be detrimental to efforts to compensate for it. Additionally, any small errors due to accelerations experienced that are not entirely vertical may compound the integration errors and potentially degrade the displacement estimate. In any case, as already discussed, a mechanical solution of this type does not seem practical on a Waveglider USV. If instead, one can measure pitch and roll, then these auxiliary measurements could be used to correct the acceleration signal generated by the microbarometer to the vertical component. But, at this point, it would be more accurate to use a full Integrated Measurement Unit (IMU) solution rather than simple double integration.

With this in mind, the envisioned solution for a motion-insensitive maritime microbarometer sensor consists of the Hyperion microbarometer, an external, synchronized and collocated IMU unit, a data acquisition system, and an adaptive filter computational process.

An IMU provides object navigation by tracking its velocity and orientation over time. This is usually done with three-axis accelerometers and three-axis gyroscopes. Such a unit can potentially provide good enough measurement accuracy of sensor heave that it may be used as a suitable reference signal to compensate for ambient pressure fluctuations. The solution is to mount a suitable IMU unit near the sensor to track its attitude and motion over time. Some IMU units are specifically designed to directly compute high accuracy heave measurements. The SBG Ekinox-A AHRS (attitude, heading, reference system), as shown in Figure 12, claims 2.5–5 cm heave accuracy [16]. Errors in heave of this magnitude correspond to errors in infrasound pressure signal estimation of 0.3125–0.6250 Pa (Equation 3). Infrasound signals larger that these levels have the potential of recovery through an adaptive subtraction process.

Figure 12. IMU capable of accurate heave measurements.

ADAPTIVE NOISE CANCELATION

An adaptive filter will be used to perform noise cancellation. A diagram of the process is shown in Figure 13. The sensor measures both the desired infrasound signal and the heave-induced pressure signal. We assume that seismic and vibration interference is already effectively suppressed by the Hyperion microbarometer decoupling scheme. The IMU independently measures a direct heave signal that we assume will be highly correlated to the heave-induced portion of the infrasound signal, plus noise. The heave signal from the IMU is converted (scaled) to the corresponding expected pressure signal (using Equation 3) and adaptively filtered prior to subtraction from the microbarometer measured signal. An adaptive feedback loop is implemented to optimally adjust the filter weights for the subtraction to account for differences in the IMU's measurement of heave and that of the microbarometer due to acceleration. Successful subtraction depends on good correlation between the two signals. The adaptation may be done using least mean squares (LMS), recursive least squares (RLS), or other approaches [17]. Tuning of the adaptive filter parameters will be required. The process is robust to the differing noise processes and any potential signal mis-synchronization between the signals. The resulting output pressure signal will represent the infrasound signal without the heave corruption.

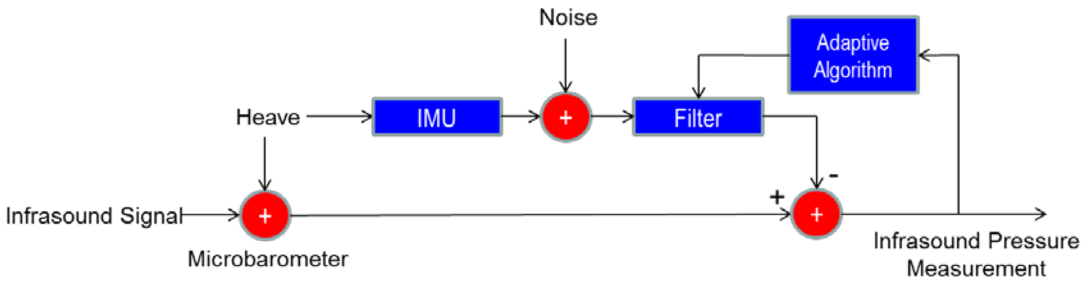


Figure 13. Diagram of the interference cancellation filter algorithm.

DATA EXAMPLE FROM AIR TO WATER 2015 EXPERIMENT

Initial testing of heave compensation method was performed with data collected during the Air to Water 2015 (A2W'15) at-sea experiment conducted on May 4, 2015. A microbarometer was fielded on board the R.V. *Acoustic Explorer* (AX) research vessel, shown in Figure 14, as it operated near San Clemente Island (off southern California). The microbarometer was installed on the upper afterdeck of the AX. For this trial, an Advanced Navigation [18] Spatial IMU was and installed, within about 1 to 2 feet from the microbarometer. The microbarometer collected pressure and acceleration signals during the operations. The IMU concurrently collected x/y/z accelerometer and gyro data, and fused this with Global Positioning System (GPS) signals to compute position and displacement measurements. In addition, the Spatial IMU unit performed real-time processing of the raw sensor data to compute a heave estimate (with specifications stating accuracy to within (the greater of) 5 cm or 5%. The observed sea state was 2 to 3, with wave heights of about 1 to 2 meters during the experiment.

Figure 14. *Acoustic Explorer* research vessel.

Figure 15 shows the heave as measured aboard the AX from both the microbarometer and Spatial IMU. The Hyperion data was recorded with a 2-kHz sample rate, and the pressure signal was converted to heave in meters by multiplying by $-12\ Pa/m$ and filtered with a low-pass filter with a 30-Hz cutoff frequency. The Spatial data was recorded at a sample rate of 20 Hz, and the heave computed by the sensor is shown with no additional filtering.

Note that the two signals match very closely in overall content and period. There is a slight phase offset, with the Spatial lagging by 1 to 2 seconds, likely caused by a delay resulting from the processing performed by the Spatial sensor. Also, the Hyperion heave estimate is 2 to 3 times larger in amplitude than the Spatial. This increase is possibly due to the complex motion of the ship (e.g., pitch and roll) affecting one or both of the sensors' measurements. In addition, a magnetic calibration was not performed on the Spatial unit once it was installed on the boat. It is possible that local magnetic fields generated by the boat's infrastructure affected the sensor's measurements. The additional infrasound content present in the microbarometer data that may contain signals of interest is observable superimposed on the low-frequency swell. Figure 16 shows the spectrums of each of the heave signals just presented. The spectral shape over the sea surface spectra region (0.03–0.30 Hz) for both signals if very similar, indicating the microbarometer output is dominated by the sea surface heave. However, content in the microbarometer is significantly higher than what is sensed by the IMU between 0.3 and 10 Hz, outside the sea surface spectral band, again indicating the presence of infrasonic content that is not motion related. The predominant peak near 0.05 Hz matches the ~ 20-second swell observed in the heave measurements. The spectral content also matches well with that expected from documented sea spectra shown in Figure 6.

Figure 17 shows the (vertical) acceleration signals as measured by the two sensors. As discussed, the Hyperion microbarometer is only sensitive to physical acceleration perpendicular to the mounting surface of the sensor (local vertical). The raw Z-axis (vertical) channel is plotted for the Spatial unit. Due to the much higher sample rate of the Hyperion data, there is a lot of high-frequency acceleration content (most likely vibrations in the ship and/or mounting) that is not present in the Spatial data. A low-pass filtered version (30-Hz cutoff) is also shown to eliminate this noise and compare the motion-induced acceleration with Spatial IMU data. We observed very good correlation between the two, with almost exact frequency and phase matching. In addition, the amplitude matches almost exactly as well. This match appears to confirm that the calibration and conversions of the microbarometer data is correct and not the cause of the amplitude mismatch observed in Figure 15. Note that the primary period of the acceleration oscillation is approximately 4.3 seconds, or a quarter of that of the heave oscillation. This indicates the complex motion of the ship and is likely an alternative wave mode being sensed, and corresponds to the bump in the spectra around 0.2 Hz.

As discussed in Section 5, in theory, the vertical acceleration signal could be double-integrated to obtain an estimate of vertical displacement. This technique was performed on both acceleration signals (microbarometer and IMU Z-axis), with intermediate removal of residual means, to evaluate the potential of such an approach. As is evident from Figures 18 and 19, even within the first few minutes the drift of the integrated solution becomes unusable as a heave estimate. This observation confirms that the aiding of an external IMU is required if infrasound signals are to be extracted from a frequency band that corresponds to the physical motion of the sensor (the wave spectra in this case).

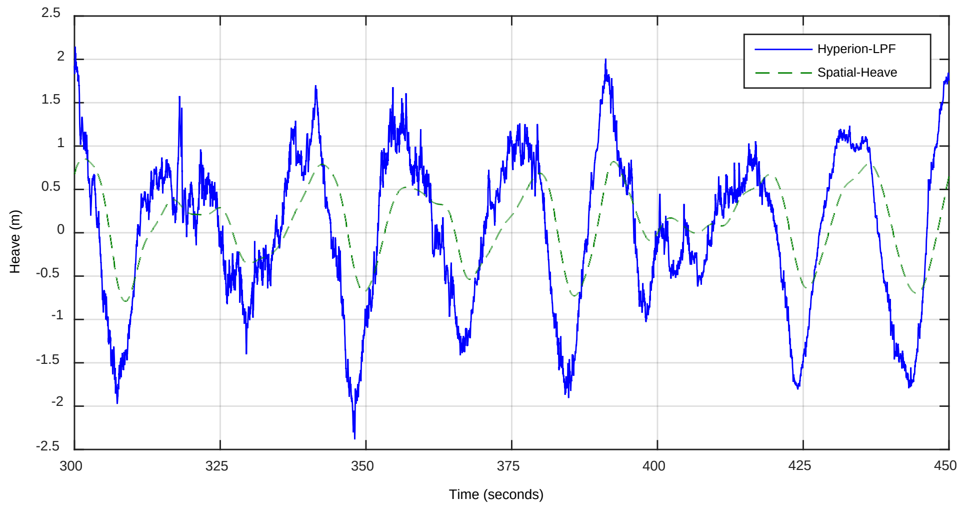


Figure 15. Comparison between the IMU heave measurement and the heave estimate derived from the microbarometer pressure measurement.

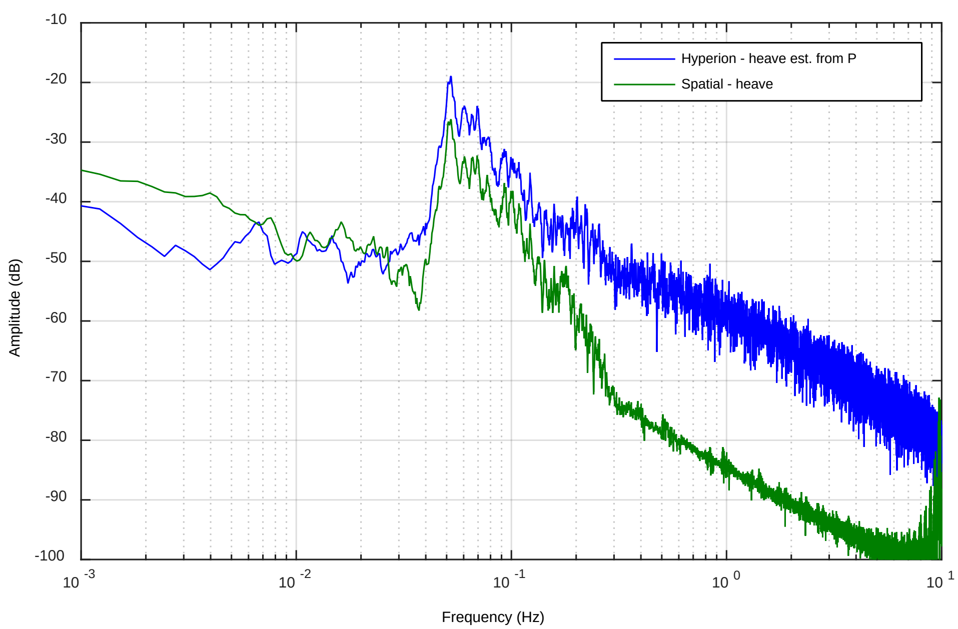


Figure 16. Comparison of the spectra of the heave signals in Figure 15.

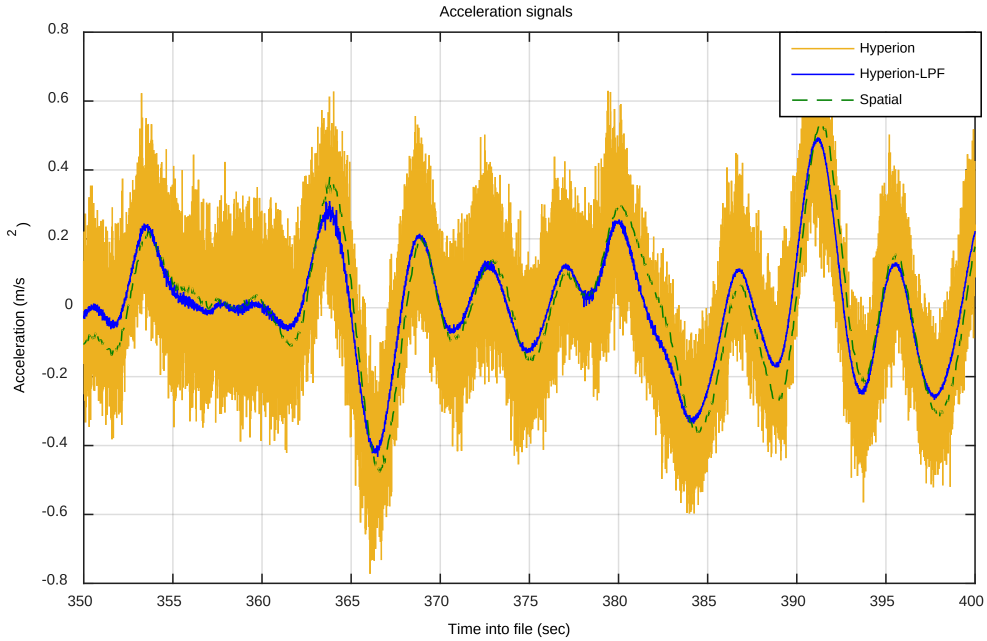


Figure 17. Comparison of the IMU Z-axis acceleration signal and the microbarometer acceleration signal.

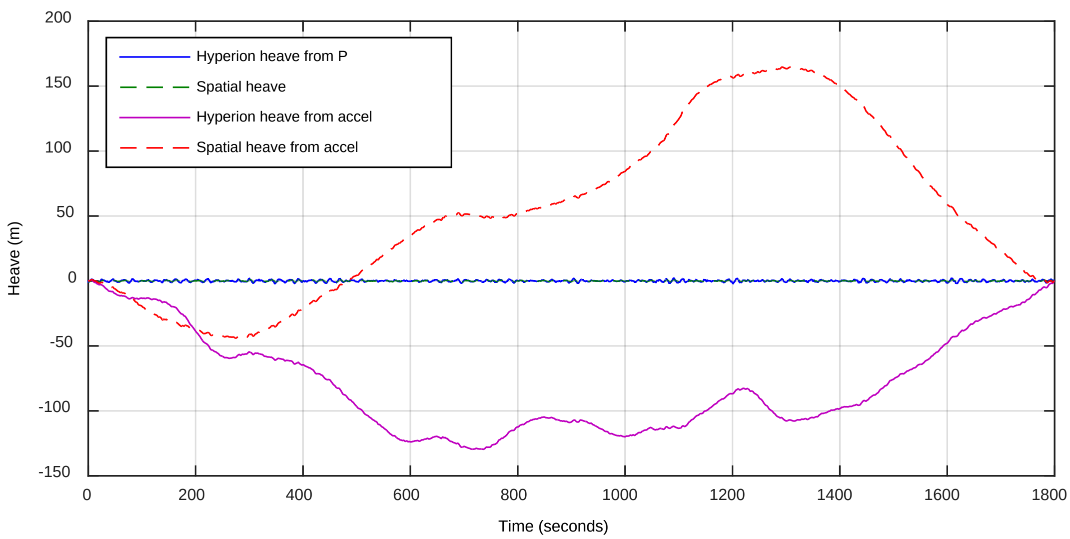


Figure 18. Comparison of the direct heave measurements with that obtainable from double-integration of the acceleration signals.

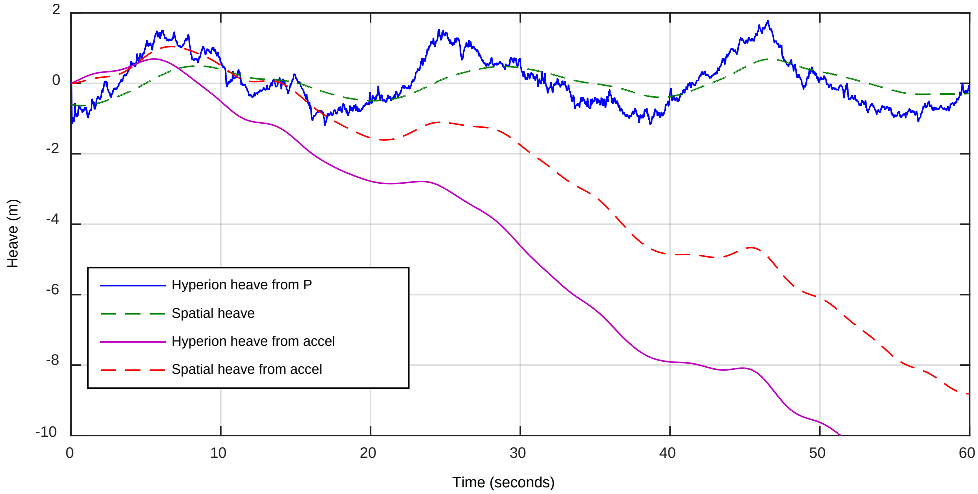


Figure 19. Zoomed view of the first minute of Figure 18.

SUMMARY

The advent of persistent ocean-going surveillance unmanned surface vehicle (USV) technology has enabled infrasound measurement within the maritime environment. The capability to monitor infrasound signals from the ocean environment will enable better worldwide coverage of infrasound signals of interest and provide better detection, classification, and localization of their sound sources. This report discussed challenges to overcome in operating in the maritime environment and issues involved in mitigating motion effects of the sensor. We showed that a significant portion of the infrasound band will be contaminated with interfering heave-induced pressure fluctuations and described an approach that combines an Integrated Measurement Unit (IMU) with the microbarometer to compensate for this motion. Preliminary data collected aboard a ship show good correlation between the measured spectra of the pressure signal and the heave measurement. Some discrepancies between the pressure signal and the IMU heave signal amplitude require further investigation.

The SSC Pacific team recommends to continue developing a heave interference cancellation system for the microbarometer so the team can build a maritime infrasound sensor. This effort will involve implementing an improved robust IMU for better accuracy. Once an external high-quality estimate of heave is obtained, an adaptive interference cancellation algorithm will be developed and applied. Additional data collection and experimentation is required. Once this phase has been demonstrated, approaches to counter wind noise and operate multiple sensors as an array will be developed.

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14. ABSTRACT

The objective of the Measurement of Infrasound from the Maritime Environment project team at Space and Naval Warfare Systems Center Pacific (SSC Pacific) is to develop an infrasound sensing capability that can operate from the maritime environment. Infrasound monitoring stations are normally situated on land-based sites. Because two thirds of the earth's surface is composed of oceans, a functional maritime-based infrasound sensing capability would greatly enhance the ability to monitor natural and anthropogenic sources of infrasound around the world.

Ocean heave, as measured by the sea surface spectrum, is shown to occupy a significant portion of the infrasound receive frequency band. Measurements were taken with a microbarometer fielded on board a ship during an at-sea experiment. The collected sound pressure data shows the interference effects of ocean heave, which are due to the change in the background atmospheric pressure as the sensor moves up and down. An external inertial measurement unit (IMU) was used to estimate the heave, and was highly correlated with the pressure interference signal.

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